The impact of land use/land cover changes and hydraulic structures on flood recession process
Chun Chang and Ping Feng

ABSTRACT

Intensified human activities have brought about great changes in runoff generation and convergence. As a significant part of the hydrological process, recession flows represent the capacity of a river basin to store rain and drain it during dry periods; therefore study of the influence of human-induced factors on flood flow recession is of great importance. The Fuping sub-catchment was selected as the study area. Comparisons of land use/land cover and soil moisture storage capacity changes were made between reference and impaired periods. In addition, 64 recession flows during 1958–2005 were simulated using the linear and non-linear reservoir recession models. Then the influence of land use/land cover changes and hydraulic structures on recession flows was identified. Results showed that grassland and cultivated land declined in area while forests increased. At the same time, there was a sharp increase in the soil moisture storage capacity. The non-linear recession model, being more accurate than the linear recession model, was used to simulate the recession process. Compared with recession curves before 1980, the initial outflow from the basin declined while the power law coefficient and recession duration increased; the power law exponent was relatively constant. Furthermore, the shapes of recession curves were flattened.

Key words | flood recession, Fuping river basin, hydraulic structures, land use/land cover changes, soil moisture storage capacity

INTRODUCTION

With rapid development of economy and society, the impact of human activities on hydrological components (such as infiltration, evapotranspiration and runoff) of a river basin, in northern China, has increased over time (Bao et al. 2012). Human-induced effects mainly include changes in land use and construction of hydraulic structures. In the hydrological cycle, the impact of land use/land cover on hydrological processes is mainly reflected in soil surface evaporation, the soil water regime and vegetation interception, thus effecting the water balance (Alaoui et al. 2014). Building of water-retaining works like reservoirs and check dams (small dams built across a channel or river to counteract erosion through reducing water flow velocity), increases the surface area and then evapotranspiration increases, while surface runoff is retained. Therefore, it is essential to detect the influence of human activities on runoff generation and convergence through analysis of hydrological data (Price 2011).

Baseflow recession, which is an integral part of the hydrological cycle, is a continuous draining and receding process in a period with little rain (Biswal & Nagesh 2013). Changes in hydrological process caused by human interference will have a direct effect on recession flows. Recession curves can provide much information about a river basin, including aquifer features. Due to the difficulty in assessing the groundwater system directly, analysing recession curves has become an indirect but effective way to collect information about groundwater hydrological processes (Stewart 2014).
Research on the effect of human activities on flood flows were mainly carried out through hydrological models and trend analysis (Benito et al. 2010; Cammerer et al. 2013). Zhang et al. (2011) identified trends and change points of the annual streamflow in the Hun–Tai River basin, Northeast China and estimated the effects of climate variability and human activities on streamflow using statistical analysis. Adnan & Atkinson (2011) identified streamflow changes in Kelantan river, Malaysia, using the Mann–Kendall non-parametric method and analysed probable causes, such as precipitation and land use changes. Li et al. (2012) used a SWAT (Soil and Water Assessment Tool) model to simulate the impacts of land use changes on annual and monthly runoff in the middle and upstream reaches of Taoerhe River basin, Northeast China, in wet, average and dry years. Li & Feng (2011) established a hydrological model for the Daqing River, China, to quantify effects of land use changes on flooding. However, recent studies mainly focused on the impact of human-induced factors on stream flow and seldom discussed recession processes. The study of recession flows contributes to baseflow separation and convergence calculation of subsurface runoff, providing important evidence for assessment of groundwater system.

This study aims to quantify the effect of land use/land cover changes and hydraulic structures on flood recession process in the Fuping river basin by model simulation. First, land use/land cover and soil moisture storage capacity changes before and after 1980 were analysed. Sixty-four recession flows selected from 1958 to 2005 were fitted by linear and non-linear recession models. Then changes in slopes and parameters of recession curves were identified.

CASE STUDY

Study area

The Fuping river basin is located in the southern branch of Daqing river, Haihe river basin and lies between 113°45’ and 114°32’E and 38°39’ and 39°8’N with a drainage area of 2,239 km² (Figure 1) (Li & Feng 2010a). As a mountainous area, the altitude increases from the southeast to the northwest; slopes are mainly over 25°. The altitudes of mountains within the Fuping river basin range from 200 to 2,286 m; geomorphic differences are noteworthy with steep mountains and deep valleys.

Fuping belongs to the north temperate continental monsoon climate zone. It has four distinct seasons: spring and winter are always dry while summer is hot and rainy. As a well-known rainstorm centre in north China, the multi-year average precipitation of the Fuping river basin is 625 mm and the precipitation from June to September accounts for 82.9% of the whole year (Li et al. 2012).

As an important tributary upstream of the Haihe river basin, the runoff in the Fuping river basin has shown an obvious decreasing trend in recent decades (Li & Feng 2010a; Chen et al. 2011). In addition to meteorological factors, such as precipitation, human-induced factors, especially the construction of large numbers of water conservation projects in the late 1970s, had significant impact on runoff.

There are 11 small reservoirs in the Fuping river basin, most of which were built in the late 1970s and mainly used for flood control and irrigation. They have a control area of 125 km² and their total capacity is 591.5 × 10⁴ m³, of which 316.7 × 10⁴ m³ is utilizable capacity. There are also 76 small dams, with available capacity of 148 × 10⁴ m³, and its irrigation area is 2.2 km². To prevent water loss and soil erosion from worsening, by the end of 2009, over 6,000 check dams
were built in Fuping. Due to the numerous water storage projects, the effects of flood control and sand blocking were remarkable. In addition, waterlogging and droughts were under effective control, which boosted agricultural output.

**Data**

Remote sensing data of land use and a digital elevation model for 1970, 1980 and 2000 were provided by the Institute of Remote Sensing Applications, Chinese Academy of Sciences. For analysis of land use/land cover changes, land use in Fuping was classified into five types: grassland, forests, cultivated land, water area (i.e. lakes, rivers and swamps) and construction land.

The precipitation and runoff data for 1958–1982 were from the China Hydrological Yearbook; data from 1983 to 2005 were provided by Water Resources Reconnaissance Office of Hebei Province. The precipitation data in the Fuping river basin are hourly areal mean rainfall calculated with data from 11 precipitation stations using Thiessen polygons (Zuo et al. 2014).

In the simulation of the flood recession process, 64 recession flows during 1958–2005 were selected; the principal of data selection is that there is no rain during recession processes in practice, this means as long as the precipitation per hour is no more than 0.1 mm (Thomas et al. 2015).

In the Haihe river basin, it is generally recognized that the influence of human activities on hydrological features before 1980 was slight; however, there was an evident intensification after 1980 (Xu et al. 2014; Lu et al. 2015). Therefore, the flood recession data series in Fuping river basin was divided into two parts: before and after 1980, and it was used in the analysis of the impact of land use/land cover and soil moisture storage capacity changes on flood recession features.

**METHODS**

**Land use/land cover changes**

According to remote sensing images and topographic map (1:100,000) in 1970, 1980 and 2000, based on ArcGIS and SWAT, areas of five land use types were extracted and their variations were analysed.

**The soil moisture storage capacity change**

To detect the impact of hydraulic structures on flood flow recession of the Fuping river basin, changes in soil moisture storage capacity of the catchment should be calculated. However, there were too many check dams to obtain their storage capacities directly; therefore, observed historical rainstorm and flood data were used for estimation.

The Fuping river basin is a semi-humid and semi-arid area with high vegetation coverage rate and infiltration capacity. Runoff generation mechanisms in this basin include infiltration-excess and saturation-excess in the same flood event. Huang et al. (2015) simulated flood processes in the Fuping river basin and discovered that differences between the simulation results of the excess saturation runoff model and compound runoff model were negligible, so in this study the analysis of soil moisture storage capacity changes was based on the rainfall–runoff curve under the assumption of saturation-excess runoff generation.

Most of the hydraulic structures in the Fuping river basin were constructed in the late 1970s; moreover, research showed that change points of annual flood peak and volume time series in the Haihe river basin centred around the late 1970s and early 1980s (Chen et al. 2011; Wang et al. 2011a, 2011b, 2013), which suggested that under human intervention, hydrological features changed a lot in this period. In the Fuping river basin, by the Pettitt test, Li et al. (2014b) found that 1979 was the change point of flood peak series. Therefore, we divided the whole period into a reference period (before 1980) and impaired period (after 1980). Several large flood events and the corresponding rainstorms were selected in the reference and impaired periods, respectively, and rainfall–runoff relation curves could be fitted (Figure 2). When a river basin is saturated, the relation between rainfall and runoff is linear, which means all rainfall is transferred into runoff. In this situation, when precipitation is the same, the difference between the runoff before and after 1980 (ΔR) was the soil moisture storage capacity change in the Fuping river basin.
Recession models

Sixty-four recession processes were selected from observed runoff data for 1958–2005 and were simulated using two recession models: the linear reservoir recession model (Safeeq et al. 2015) and the non-linear recession model (Charron & Ouarda 2015).

Linear reservoir recession model

Suppose there is a linear relationship between $Q$ and $S$:

$$Q = mS$$

where $Q$ is the outflow from the basin (m$^3$/s), $S$ is the volume of water stored (m$^3$) and $m$ is a recession parameter (1/d). Combined with the equation of continuity:

$$\frac{ds}{dt} = -Q$$

we get the equation of recession flow:

$$Q = Q_0 \exp (-mt)$$

where $Q_0$ is the initial outflow from the basin (m$^3$/s) when $t = 0$, $t$ is time.

Non-linear recession model

Suppose $Q$ and $S$ follow a power law relationship:

$$S = aQ^b$$

where $a$ and $b$ are constants.

When $S$ is substituted into Equation (2), we get:

$$abQ^{(b-1)} \frac{dQ}{dt} = -Q$$

After the rearrangement of Equation (5), we get:

$$\frac{dQ}{dt} = \frac{1}{ab} Q^{2-b}$$

Suppose: $1/ab = k$, $2 - b = \alpha$, we get:

$$\frac{dQ}{dt} = kQ^{\alpha}$$

where $k$ is the power law coefficient and $\alpha$ is the power law exponent.

Accuracy of the two models was evaluated by loss function (Li & Feng 2010b), using the formula:

$$\varepsilon_r^2 = \frac{1}{nt} \sum_{i=1}^{nt} \left[ \frac{1}{ni} \sum_{j=1}^{ni} r_{ij}^2 \right]$$

where $r_{ij}$ is the relative errors between observed and simulated $Q$ of the $i$th recession curve and the $j$th time period, $ni$ is the number of observed data of the $i$th recession curve and $nt$ is the number of recession curves. The less the loss function value is, the greater is the accuracy.

Variation of recession curves

The shape of a flood hydrograph is influenced by precipitation and land surface factors, such as land use and land cover (Khaleghi et al. 2011). As for the shape of a flood hydrograph, the most intuitive parameter is the slope of the hydrograph within a certain period. For example, from $t_2$...
to \( t_3 \), the slope of the flood recession curve is as follow (Figure 3):

\[
s = \frac{(Q_0 - Q)}{(t_3 - t_2)}
\]  

(9)

where \( s \) is the slope (m\(^3\)s\(^{-1}\)h\(^{-1}\)), which shows flood recession rate. Analysing the variation trend of the time series of slopes helps understanding of the changes in the shape of recession curves.

In this paper, the nonparametric Mann–Kendall test (Zang & Liu 2013) was used to detect the trend of hydrograph slope from 1958 to 2005. In the Mann–Kendall test, the null hypothesis \( H_0 \) is that \( U_F i \) is not statistically significant. The test statistic \( U_F i \) is formed as follows:

\[
UF_i = \frac{S_i - E(S_i)}{\sqrt{\text{Var}(S_i)}} (i = 1, 2, \ldots, n)
\]  

(10)

\[
S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \ldots n)
\]  

(11)

\[
r_i = \begin{cases} 
1, & x_i > x_j \\
0, & x_i \leq x_j \end{cases} \quad (i = 1, 2, \ldots i - 1)
\]  

(12)

\( x_i \) is an independent and identically distributed random variable with \( n \) samples. The expected value and variance are calculated as follows:

\[
E(S_i) = i(i - 1)/4
\]  

(13)

\[
\text{Var}(S_i) = i(i - 1)(2i + 5)/72
\]  

(14)

On a significance level of \( \alpha \), the null hypothesis \( H_0 \) is accepted if \(|U_F i| < U_{\alpha/2}\), where \( U_{\alpha/2} \) is standard normal deviates. In contrast, if \(|U_F i| > U_{\alpha/2}\), \( U_F i \) is statistically significant. A positive \( U_F i \) value denotes a positive trend, and a negative \( U_F i \) value denotes a negative trend.

**RESULTS**

**Analysis of land use/land cover changes**

Remote sensing images of land use/land cover in 1970, 1980 and 2000 are shown in Figure 4, and the land use/land cover changes in the Fuping river basin are summarized in Table 1.

The main land use/land cover types in Fuping were grassland and forests, which accounted for more than 90% of the total area. From 1970 to 1980, there was an obvious decrease in cultivated land with a value of 48.16%, while forests increased by 24.63% and grassland changed slightly (3.11%). Lakes, rivers and swamps and construction land have disappeared since 1980.

In 2000, forests had increased by 0.13% while grassland and cultivated land decreased by 0.04% and 0.71%, respectively. It can be seen that land use/land cover changes in Fuping river basin during 1980–2000 were slight, and most came from cultivated land.

It is worth mentioning that there was a significant decrease in water area from 1980. Many studies in variations of precipitation in the Haihe river basin (Wang et al. 2011a; Bao et al. 2012) showed that significant downward trends were observed in annual series of precipitation over the past 50 years. Furthermore, the sharp decrease of precipitation during the flood season in the late 1970s lead to the drop in annual precipitation after 1980 (Wang et al. 2011b). The downtrend of annual precipitation in the Fuping river basin is consistent with that in the Haihe river basin (Chen et al. 2011). Therefore,

![Figure 3 | Sketch map of the slope of flood hydrograph.](http://iwaponline.com/jwcc/article-pdf/8/3/375/375355/jwc0080375.pdf)
as can be seen from Figure 4(b), water area disappeared since 1980.

Generally, the most significant changes of land use/land cover before and after 1980 were the rise in forests and drop in cultivated land, which mainly took place during 1970–1980. Since 1980, proportions of land use types stayed almost the same.

**Analysis of soil moisture storage capacity change**

In addition to land use/land cover changes, the large number of reservoirs and check dams for soil and water conservation was another main factor related to changes in flood process.

In the Haihe river basin, research on the Zijingguan river basin (Li & Feng 2014), which is close to the Fuping river basin, showed that both flood peak and volume decreased as a result of land use changes and hydraulic structures, and although the transfer of land use types had minor effects on floods, the increase of soil moisture storage capacity was the main cause. Therefore, hydraulic structures are likely to have impacts on flood recession processes in the Fuping river basin.

However, due to the difficulty in observing and simulating runoff processes in channels with check dams, hydrological responses are still unclear in river basins with large numbers of check dams and small hydraulic structures. In addition, check dams in China are generally built to meet the needs of the residents lacking long-term design schemes, and there are hardly any records of locations, storage capacities or outflow methods of check dams (Li et al. 2014a). Therefore, storage capacities of small reservoirs and check dams must be estimated according to precipitation and runoff data.

Twenty rainfall-runoff datasets before 1980 and another 20 after 1980 were plotted (Table 2) and rainfall–runoff relation curves were fitted (Figure 5). The root mean square errors before and after 1980 were 3.32 mm and 2.70 mm, respectively; in addition, average relative errors between fitted and observed runoff values were 16.18% and 17.45%, which indicated good curve fitting results. When the whole river basin is saturated and precipitation is the same, the difference of the generated runoff before and after 1980 was 7.1 mm. As can be seen from Figure 5, the soil moisture storage capacity after 1980 went up by

![Figure 4](http://iwaponline.com/jwcc/article-pdf/8/3/375/375355/jwc0080375.pdf)
1,567.3 × 10^4 m³, which was more than the total capacity (591.5 × 10^4 m³) of 11 small reservoirs and dams constructed before 1980 in Fuping, suggesting that other water conservation projects, such as check dams, had a significant impact on the increase of the soil moisture storage capacity. Although errors may exist in the process of curve-fitting, the calculated results were still of great importance to show an upward trend of the soil moisture storage capacity.

**Impacts on flood recession**

**Changes in slopes of recession curves**

We calculated the slope for three different parts of the recession curves. As can be seen in Figure 6, from 1958 to 2005, slopes of recession curves generally showed a significant decreasing trend at α = 0.05 level. In addition, there was a sharp decrease for UF values from 1965 to 1980, which indicated that the shapes of recession curves changed a lot, that is, flattened.

The mean slopes before and after 1980 for different Q values are shown in Table 3. It is clear the average slopes after 1980 were much less than that before 1980, which indicated the tendency of recession curves to flatten. Besides, the average slopes went down as Q values were decreasing.

**Table 1 | Land use/land cover changes in the Fuping river basin**

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<thead>
<tr>
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</thead>
<tbody>
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<td>Area</td>
<td>Proportion (%)</td>
<td>Area</td>
<td>Proportion (%)</td>
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<td>Cultivated land</td>
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<td>34.06</td>
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For the linear recession model, m was between 0.0043/d and 0.0991/d; for the non-linear recession model, the mid-value of α was 2.075, and k was between 0.0000185 and 0.0147. Loss function values of two models are shown in Table 4; it is clear that the non-linear recession model was more precise with a loss function value of 2.829 m³/s. In addition, simulation results of four random recession flows are shown in Figure 7; it is evident that simulated values of non-linear model were closer to observed values.

**Changes in parameters of recession curves**

During 1970–2000, grassland and cultivated land declined while forests showed an upward trend. Afforestation will increase vegetation interception, evapotranspiration and soil infiltration and moisture content, thus reducing runoff (Qian et al. 2015). Moreover, during early and late flood seasons and dry periods, reservoirs and dams need impounding, so most of the precipitation is retained by hydraulic structures, thus runoff decreases, which has an effect on recession processes.

As many small reservoirs and check dams were built around 1980, recession flows before and after 1980 were analysed separately. Mean values of initial outflow from the basin (Q₀) before and after 1980 were 64.63 m³/s and 48.06 m³/s (Table 5), respectively. In addition, it is clear from Figure 8 that Q₀ after 1980 was generally lower than that before 1980, showing the descending trend in Q₀.

Besides Q₀, k also decreased while recession duration became longer. Due to the increase of forests and construction of hydraulic projects during 1970–2000, more surface water was retained, which led to the uptrend of infiltration, and consequently the recession duration was longer.
Table 2 | Dataset of observed and fitted runoff before and after 1980

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<tr>
<th>Date</th>
<th>P - Pa (mm)</th>
<th>R (mm)</th>
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<tr>
<td>30.07.1996</td>
<td>300</td>
<td>123.34</td>
<td>120.05</td>
<td>2.66</td>
</tr>
<tr>
<td>10.07.1999</td>
<td>87.8</td>
<td>3.69</td>
<td>4.66</td>
<td>26.14</td>
</tr>
<tr>
<td>13.08.1999</td>
<td>164.87</td>
<td>25.82</td>
<td>23.83</td>
<td>7.70</td>
</tr>
<tr>
<td>17.08.1999</td>
<td>136.98</td>
<td>12.81</td>
<td>14.74</td>
<td>15.03</td>
</tr>
<tr>
<td>Average relative error</td>
<td></td>
<td></td>
<td></td>
<td>17.45</td>
</tr>
</tbody>
</table>
Compared with other parameters, the variation of $\alpha$ was slight, which verified Biswal & Nagesh’s (2014) finding that $\alpha$ of a basin had links with its channel network morphology and generally remained constant.

**DISCUSSION**

It has been widely acknowledged that land use/land cover changes (Price 2011; Huang et al. 2016) and anthropogenic activities (Gao et al. 2011; Ye et al. 2013) can have important impacts on baseflow by changing evapotranspiration, infiltration and the storage capacity of a watershed. As an integral part of baseflow, studies on baseflow recession processes, especially the changes in characteristics of recession curves are essential in making accurate assessment of the subsurface systems. The present analyses mainly focus on dynamic behaviours of recession flows (Wang 2011; Shaw et al. 2013). Biswal & Nagesh (2014) investigated the dynamic relationship between $-\frac{dQ}{dt}$ and $Q$ of a basin using the geomorphological recession flow model, which incorporates the temporal evolution of the drainage network. Wang & Cai (2010) discussed the impact of groundwater pumping, water diversion and return flow on the determination of the recession slope curve and the cloud shape of the data points of $-\frac{dQ}{dt}$ and $Q$.

However, few studies involve effects of land use/land cover and hydraulic structures on recession curves. In the present research, the study period was divided into a reference period (before 1980) and an impaired period (after 1980) because of intensifying human activities in late 1970s and early 1980s in the Fuping river basin (Li et al. 2014b). Changes in land use and soil moisture storage capacity were identified, then comparisons were made
between recession curves before and after 1980. On account of the large number of hydraulic structures and check dams, observed rainstorm and flood data were used to estimate changes in soil moisture storage capacity of the Fuping river basin. The increasing trend of soil moisture storage capacity in the Fuping river basin was consistent with the results of Li et al. (2014a), who selected five large rainstorms from the 1950s to 1990s, before which there was no rain for 15 days, then calculated the soil moisture storage capacity values for each selected rainstorm. Nevertheless, the difference between the soil moisture storage capacity in 20 July 1977 and 30 July 1988 was 6 mm, less than that before and after 1980 (7.1 mm) in this paper. Compared with the study of Li et al. (2014a), the results in this study were more convincing because more data (40 rainstorms) were selected to calculate the soil moisture storage capacity change. Although bias may exist in the estimation, the results in this study were still very useful for characterizing the general variation trend of the soil moisture storage capacity in the Fuping river basin.

In this study, a non-linear recession model was adopted in the simulation of recession flows in the Fuping river basin, then changes in slopes and parameters of recession curves before and after 1980 were analysed. In traditional studies on recession models, researchers generally assumed a unique relationship between storage and discharge, or \(-dQ/dt\) and \(Q\) (Harman et al. 2009; Thomas et al. 2013). Furthermore, \(a\) and \(k\) are usually obtained from the curve-fitting results of data from all selected recession events. However, taking certain \(a\) and \(k\) as representative values of the basin and establishing a unique equation between \(-dQ/dt\) and \(Q\) is improper considering human impacts, evapotranspiration, observational errors, overland flows mixed with subsurface flows and other uncertainties. Biswal & Marani (2010) found that the power law exponent \(a\) of recession curves in a basin depended on the channel network morphology and remained relatively constant while \(k\) varied greatly in different recession events. Therefore, it is more reasonable to analyse recession curves of a basin individually, which will better reflect the dynamic behaviour of recession flows. In this study, the median of \(a\) was regarded as the representative \(a\) in the Fuping river basin, and the range of \(k\) values was shown. However, the non-linear recession model used in this paper could be improved by considering

Table 3 | Average slopes before and after 1980

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Before 1980</th>
<th>After 1980</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_0) (m³/s)</td>
<td>64.63</td>
<td>48.06</td>
</tr>
<tr>
<td>(k)</td>
<td>(2.64 \times 10^{-4})</td>
<td>(7.76 \times 10^{-4})</td>
</tr>
<tr>
<td>Recession duration (h)</td>
<td>74</td>
<td>78</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>2.045</td>
<td>2.105</td>
</tr>
</tbody>
</table>

Table 4 | Simulation parameters and loss function values of two models

<table>
<thead>
<tr>
<th>Models</th>
<th>Parameters</th>
<th>Loss function values ((\varepsilon_r))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear recession model</td>
<td>(m = 0.0043/d-0.0991/d)</td>
<td>3.025</td>
</tr>
<tr>
<td>Non-linear recession model</td>
<td>(a = 2.075, k = 0.0000185–0.0147)</td>
<td>2.829</td>
</tr>
</tbody>
</table>

Figure 7 | Simulation results of four random recession flows.
human interventions; moreover, the proportions of land use/land cover and hydraulic structures in the impacts on recession process were not quantified and deserve further research.

CONCLUSIONS

This study analysed land use/land cover and soil moisture storage capacity changes in the Fuping river basin and their impacts on recession flows.

Results showed that during 1970–1980, forests increased by 24.63% while grassland and cultivated land decreased by 3.11% and 48.16%, respectively. However, land use/land cover changes from 1980 to 2000 were slight: forests increased by 0.13% while grassland and cultivated land declined by 0.04% and 0.71%. Due to construction of hydraulic structures, the soil moisture storage capacity in the Fuping river basin after 1980 went up by $1.567.3 \times 10^4$ m$^3$ compared with that before 1980.

During 1958–2005, slopes of recession curves were decreasing significantly, which indicated that recession curves were flattening. Average slopes after 1980 were less than that before 1980. In addition, the slope of a recession curve is increasingly gentle during a flood recession process.

In the simulation of recession curves, loss function values were used to evaluate the precision of linear and non-linear recession models; the values were 3.025 m$^3$/s and 2.829 m$^3$/s, respectively. Therefore, a non-linear recession model was adopted for simulating recession flows in the Fuping river basin.

Comparisons of parameters were made between recession curves before and after 1980: $Q_0$ went down while $k$ and recession duration increased, and $\alpha$ was relatively constant. The above variations were mainly owing to the increase of forests and construction of hydraulic structures, especially small reservoirs and check dams.

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REFERENCES


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